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Critical choices and the politics of decarbonization pathways: Exploring branching points surrounding low-carbon transitions in Canadian electricity systems

Daniel Rosenbloom[a,*], Brendan Haley[b], James Meadowcroft[a]

[a] School of Public Policy and Administration, Carleton University, 1125 Colonel By Drive, Ottawa, K1S 5B6, Ontario, Canada
[b] School for Resource and Environmental Studies, Dalhousie University, 6100 University Ave, Halifax, B3H 4R2, Nova Scotia, Canada

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ABSTRACT

Transition pathways have attracted increasing interest as a useful analytical lens through which to capture the interlocking processes, patterns, and directions that might constitute substantial movement toward sustainability. While recent research has elaborated the political character of pathways, there is still room to further scrutinize the role of *critical choices* and *branching points* in defining diverging pathways. Contributing to the growing body of research on pathways, this study develops an approach that: (1) elaborates the dynamics that open branching points and (2) illustrates how critical choices help define the direction taken at these openings, giving rise to diverging decarbonization pathways. As part of this, the contested nature of critical choices is examined, revealing how actors struggle to shape possible trajectories. This approach is demonstrated by exploring unfolding low-carbon pathways in Canadian electricity systems, drawing lessons for the practice and theory of pathways. In particular, findings indicate that attending to branching points more explicitly exposes the implications and trade-offs embodied within choices by linking near-term decisions to long-run low-carbon configurations.

1. Introduction

Mitigating the most serious impacts of climate change implies a radical transition from high-carbon energy configurations to low-carbon arrangements by mid-century. Over the past decade, transition perspectives have emerged as an increasingly important research paradigm for contemplating this societal challenge [1]. *Transition pathways*, in particular, have attracted rising interest as a useful analytical lens through which to capture the interlocking social and technical processes, patterns, and directions that might constitute substantial movement toward sustainability [2,3]. Moving beyond traditional forward-looking techniques, transition pathways draw lessons from historical episodes of change in order to embrace complexity and the plurality of possible co-evolutionary changes in practices, rules, actor networks, technology, and culture that are likely to shape future low-carbon transitions [4]. While some analysts have focused on emerging innovations and the protected niches within which they develop as key transition pathways [5], others have developed typologies that offer a more differentiated understanding of the potential origins, influences, and directions of change [6,7]. Extending this work, more recent studies highlight how pathways are shaped by struggles among interests [8], continual agent-structure interactions [9], and sequences of decisions at branching points [10]. These contributions suggest that pathways not only relate to broad patterns and directions of change but also concern sequences of "decision making at critical points" [10]:156 and "rounds of moves and counter-moves" by contending actors [9]:898, particularly around key sites of contestation (e.g., infrastructure investment). Similarly, research bridging transition and discursive perspectives indicates that continual processes of contestation over energy choices and low-carbon pathways often take the form of framing struggles among competing actors [11]. Indeed, contending material interests, frames of reference, and visions for the future are at least as important for critical choices around energy as institutional and infrastructure rigidities [12]. Yet, while these contributions point to the inherent political character of transition pathways, there is still room to further scrutinize the role of *critical choices* and *branching points* in defining diverging pathways as well as the way in which these sites of contestation are negotiated over time.

Contributing to the growing body of work on transition pathways, this study develops an approach that: (1) elaborates the dynamics that open branching points and (2) illustrates how critical choices help define the direction taken at these openings, giving rise to diverging

* Corresponding author
E-mail address: daniel.rosenbloom@carleton.ca (D. Rosenbloom).

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decarbonization pathways. In doing so, we explore socio-technical patterns and pressures in electricity systems (illustrated by regional systems in Ontario and Quebec, Canada) and identify a series of critical choices (out to 2035) that have implications for the direction of long-term low-carbon pathways for electricity configurations (out to 2050 and beyond). Given the centrality of electricity systems for long-term societal decarbonization, we focus on electricity configurations and their linkages to emissions reductions in broader energy systems (e.g., transport and heating). Indeed, research on decarbonization pathways [13] suggests that electricity systems will need to meet vastly growing demand (due to the electrification of other energy end-uses, for instance) while simultaneously enabling rapid low-carbon system change.

This study proceeds in the following fashion. The paper begins by discussing the analytical approach, which draws together different perspectives on transition pathways. This approach is then applied to examine the socio-technical patterns, emerging pressures, critical choices, and branching points surrounding decarbonization pathways for electricity systems in Ontario and Quebec. The paper concludes by contrasting potential low-carbon pathways for the selected jurisdictions, drawing lessons for both future research and governance.

2. Critical choices, branching points, and pathways

This study draws upon diverse insights on transition pathways in order to explicate the role of critical choices and branching points. Transitions can be understood as long-term co-evolutionary processes involving the reorientation of one or more socio-technical systems such as energy or transportation [1]. These processes are often conceptualized in terms of interactions among three dimensions: the regime, niche, and landscape. The regime represents the dominant social (e.g., institutions) and material (e.g., infrastructure) configuration through which a societal function is met. The regime displays path dependent characteristics as deeply embedded social and material structures, resources, and power relations constrain current choices in a fashion which tends to reproduce existing patterns. Niches, on the other hand, embody emerging innovations along with their supporting actor networks, which are often envisioned as the loci of more radical change. The landscape represents broad developments such as shifting cultural, political, and economic conditions. Historical analysis has suggested socio-technical transitions come about when landscape developments and internal issues put pressure on the regime, resulting in windows of opportunity through which niche innovations can emerge and modify system configurations [14]. Other work, however, also points to the importance of niche-regime symbioses and even regimes themselves in driving transformations [6,7], prompting a more differentiated understanding of the ways in which transitions may unfold.

In line with this more differentiated view of transitions, a variety of studies have adopted the concept of "pathways" to engage more deeply with the plurality of low-carbon possibilities [2,3]. The growing body of work on pathways draws upon and complements scenario approaches (see [15] for an insightful discussion of low-carbon scenarios), which often serve as an input for applications of pathways [16]. Yet, studies that apply a pathways approach deviate from traditional scenarios in important ways, including their linkage to historical, prospective, and backcasting (i.e., working backward from a particular emissions target or technological configuration as a set endpoint) techniques [3]. And, from a conceptual standpoint, pathways possess distinct attributes and functions which are being leveraged by diverse research strands to call attention to different dimensions of low-carbon transitions (consider [2] for a discussion of biophysical, techno-economic, and socio-technical conceptions of pathways). Here we draw upon the *socio-technical conception of pathways* to embrace the "unfolding socio-technical patterns of change within societal systems as they move to meet human needs in a low-carbon fashion" [2]:39. In this view, the emphasis is on the way societal system configurations move from one arrangement to another over time by attending to multi-level interactions and co-evolutionary patterns.

Broadly, transition scholars have deployed socio-technical pathways to: (1) characterize patterns of historical system change ; and (2) provide insight into future sustainability transitions . With respect to the former, a prominent strand of research focuses on developing pathway typologies to elaborate the different multi-level patterns that may characterize transitions [6,7,9,17]. From this body of work, several important insights are central to our discussion. First, pathways are not comprised of one dominant pattern (e.g., niche-driven change) but rather involve a plurality of possibilities that can manifest in vastly different directions of change. In this way, pathways are uncertain as they involve complex and cascading interactions among different potential developments and interventions across multiple levels. Second, transition pathways embody both processes of continuity and discontinuity. As they describe the movement of socio-technical configurations over time, pathways exhibit the relatively well understood characteristics of path dependence and momentum [19]. However, they also display path creation tendencies that permit for the possibility of more radical change. Geels et al. [9], for instance, suggest that pathways should not be viewed as entirely self-reinforcing but rather require continuous enactment by actors (as agent behavior is influenced by and continually reproduces and produces rule systems). In this fashion, pathways are not only shaped by entrenched structures, historical contingency, and chance exogenous developments but are also endogenously influenced by contending actors as they leverage their resources (ideational and material) to frame problems and influence solutions [20]. And, as recent work shows, these competing actors often possess fluid strategies and positions rather than rigid alignments with regime or niche [21]. Third, pathways are deeply temporal [22,23] as historical contingencies, context, and deliberate action interact to modulate the shape and pace of transitions. That is, pathways involve the interplay among past, present, and future socio-technical patterns in specific contexts as sequences of choices are layered over time, creating cascading effects that set the conditions for future rounds of action.

With respect to approaches that focus principally on future transition pathways, two central strands of research have attracted growing interest. First, *socio-technical scenarios* [24] are a foundational technique for exploring future system change. According to Hofman et al. [25], socio-technical scenarios are distinguished from traditional scenario methods in that they more explicitly engage with the co-evolution of society and technology, drawing insights from innovation studies and sociology (consider [25] for a more extensive discussion of socio-technical scenarios and how they deviate from more traditional scenario methods). Often linking to the multi-level perspective and the typologies it has inspired, socio-technical scenarios focus on exploring "the way linkages between the different levels may set in motion transition paths" [24]:655. Complementing traditional scenario approaches, the aim here is to produce plausible narratives about the future co-evolution of society and technology as low-carbon transitions unfold, extending and perhaps challenging more technically-focused diffusion trajectories [26].

Building on socio-technical scenarios, a second research strand more explicitly develops an approach to explore pathways [4]. Here, the essential analytical task is to characterize multi-level interactions and specify those that may give rise to or influence pathways. As part of this, there is an effort to focus more closely on governance, highlighting the way in which pathways are shaped by competing orientations linked to diverse societal interests [18]. Perhaps most importantly however, Foxon et al. [10] elaborate how pathways "reflect the outcomes of multitudes of decisions made by interacting actors along the way". Invoking the concept of *branching points* [27], they demonstrate how actors can shape the orientation of pathways by influencing decisions around the renewal of institutional commitments and infrastructure at key moments in time. Acting as an important analytical complement to path-dependence, branching points represent potential openings in established trajectories where multiple alternative choices

are available, which could either reproduce existing trajectories or lead along new directions depending on the choice taken [28]. A branching point can therefore be understood as a window of opportunity whose outcome is defined by a politically mediated choice taken in the presence of alternatives [29]. As branching points are resolved, they orient system configurations along new or existing trajectories that endure over time, reconfiguring the envelope of future options as some possibilities are opened up and others are closed down. Taken together, this suggests that pathways not only involve socio-technical and multi-level patterns that set the broad conditions for action, but are just as fundamentally *(re)produced through sequences of actor interactions around critical choices at branching points*.

It is the dynamics that constitute, contest, and help define branching points for decarbonization pathways that this study hopes to further explore. To this end, we draw on the abovementioned perspectives to capture: (1) the socio-technical patterns (regime, niche, and landscape interactions) that surround a given system configuration; (2) the emerging pressures and tensions (internal and external to the configuration) that arise from these patterns; and (3) how these pressures open branching points for low-carbon pathways, which lead along different trajectories depending on the choices taken (see Fig. 1). In this view, branching points are constituted by patterns and pressures that are both social and material in nature (e.g., the lifespan of particular energy infrastructures but also new policy objectives). And, it is the specific choices taken in the presence of alternatives that helps to define the course adopted at a branching point (i.e., whether the configuration orients toward established arrangements or begins to set a new trajectory). Correspondingly, low-carbon pathways can be understood as encompassing cascading sequences of choices, trajectories, and consequences that together lead toward different possible system configurations in the long-run. As Fig. 1 shows, specific choices may be taken in one way or another, but they may also be delayed until they are eclipsed by different choices or alternatively cannot be further deferred. In this way, putting off a critical choice may keep certain options open and allow actors to stretch branching points (consider, for instance, how political administrations may straddle the fence on important decisions until the last moment). Yet, even though a delay may act to keep some options open for a time, certain possibilities may then no longer be attainable (e.g., if a permit or license is allowed to lapse). This approach acknowledges that while pathways are historically-layered and relate to broad multi-level patterns, it is equally important to explore how actors frame and respond to impinging pressures, how they leverage resources to influence critical choices, and how this might open up or close down different pathways along which development might proceed [30]. Indeed, branching points and the choices they embody represent key political battlegrounds. And so, a central objective of our work is to attend more closely to the way in which interests vie for position in shaping critical choices.

Beyond these theoretical considerations, a few specific decisions were made in deploying this approach. First, this analysis focuses on electricity systems (and their linkages to transport, heating, and so on) as they are often envisaged as one of the central pillars of low-carbon pathways [13]. Second, the study concentrates on near-term choices (out to 2035) with implications for long-term low-carbon pathways (out to 2050 and beyond). Third, the analysis attends to subnational electricity systems given that in Canada provincial governments are primarily responsible for the provision of electricity. These systems vary with respect to ownership, regulatory structure, technological preferences, resource endowments, electricity exports, industrial and economic activity, policy regimes, and interests. Accordingly, we select Ontario and Quebec as they have varied socio-technical characteristics, are the most populace provinces, and represent the primary sites of electricity consumption in Canada. Ontario possesses a partially liberalized electricity sector and mixed electricity supply, while Quebec can be characterized as publicly-owned and hydro-based. After briefly addressing the Canadian electricity context, the following sections detail the patterns, pressures, and choices that help constitute and define branching points for potential low-carbon pathways in the selected regional electricity systems.

Canada is a relatively lightly populated (roughly 36 million) and large northern nation (the fourth largest country in land area) with a federal parliamentary democracy and historically resource-based economy (consider [31,32] for a political economy of Canada). Canadian electricity systems have traditionally evolved in a somewhat siloed fashion given that they are principally under the jurisdiction of subnational provincial governments. Correspondingly, electrical interties have predominantly stretched along north-south lines as the provinces competed to export power to major load centres in the United States (Canada's largest trading partner). In aggregate, electricity systems in Canada have developed in a relatively low-carbon fashion (60%

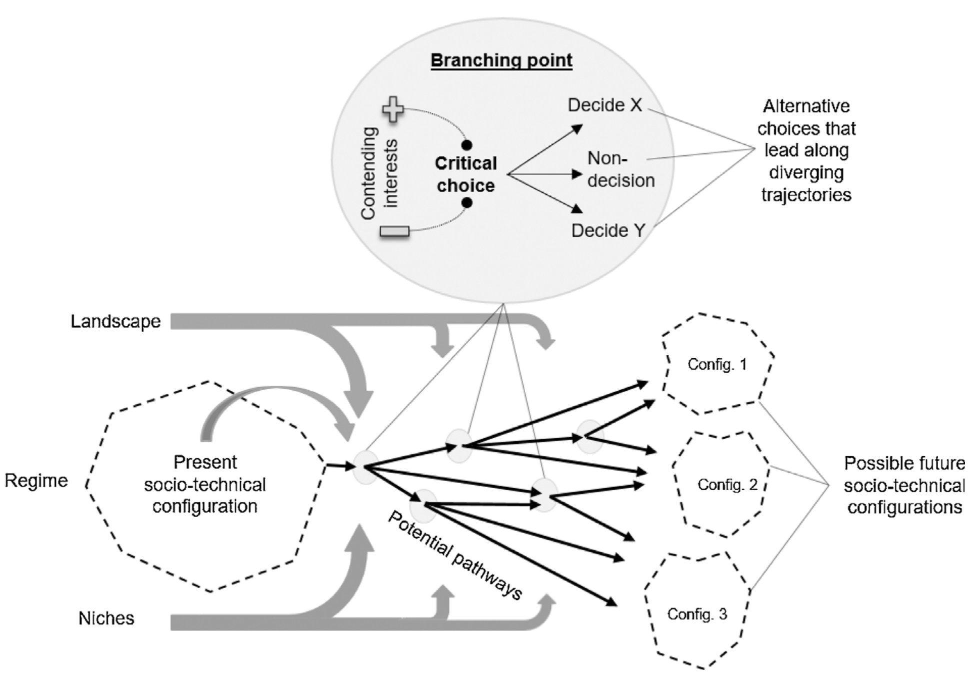


Fig. 1. How branching points are constituted, contested, and defined.
This figure depicts: (1) the socio-technical patterns that surround a given system configuration; (2) the emerging pressures and tensions that arise from these patterns; and (3) how these pressures open branching points for low-carbon pathways, which lead to alternative configurations depending on the choices taken. It also illustrates the contending interests that mobilize around critical choices and attempt to shape their outcomes.

hydroelectric, 6% other renewables, and 20% nuclear as of 2015) mainly due to vast hydroelectric resource endowments. However, low-carbon power is not evenly spread across the country as Saskatchewan, Alberta, and northern communities rely primarily on fossil fuels for electricity generation. In contrast to the United States where historically the private utility was the dominant model for electricity provision, there has typically been a much stronger role for public ownership in Canadian electricity systems (with notable exceptions such as Alberta). Electricity prices in Canada have typically been lower in comparison to jurisdictions in the United States and Europe.

3. The electricity system in Ontario

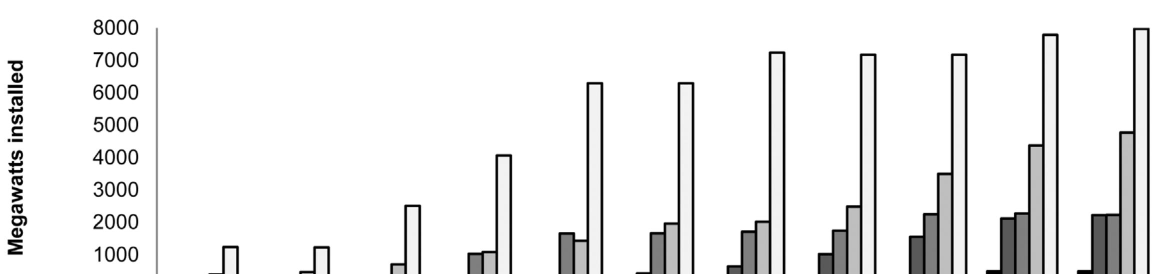
3.1. Socio-technical patterns

Two basic socio-technical patterns laid the groundwork for the current electricity configuration in Ontario: (1) an expansionist orientation that guided system planning and (2) the restructuring process of the late 1990s [8]. For much of the twentieth century, the development of the electricity configuration in Ontario was oriented around the expansionist tendencies of Ontario Hydro (the now defunct vertically-integrated public utility), which saw a layering of investments in large hydroelectric facilities (1922–1950s) followed by the construction of coal (1950s–1970s) and nuclear (1960s–1990s) megaprojects. However, the expansionist orientation promoted by Ontario Hydro collapsed in the final third of the twentieth century as electricity demand fell short of projections and the nuclear buildout suffered from cost overruns that produced a crisis of legitimacy for the public utility [33]. This crisis created the conditions for the Conservative government to restructure the sector in the late 1990s, which eroded central planning, reorganized key actor networks, and expanded the role of private investment. Yet, a liberalized market system was never fully realized and central planning functions were reintroduced when the Liberals took power in 2003.

Under successive Liberal governments (2003 to the present), the electricity configuration has been leveraged to simultaneously pursue industrial development and environmental goals [34]. In particular, policy objectives targeted the phase-out of coal-fired power (2003–2014) and the deployment of lower carbon generating sources (see Fig. 2). According to Harris et al. [35], the shift away from coal was enabled by reactor restarts at legacy nuclear stations, new natural gas units, the deployment of emerging renewables, and conservation. Alongside the coal phase-out, the Liberal government launched major initiatives in 2007 (the Renewable Standard Offer Program) and 2009 (the *Green Energy and Economy Act* with the Feed-in Tariff as its centerpiece program) to incentivize the adoption of emerging renewables and promote the development of a green energy economy [36]. While the deployment of renewables has increased considerably under this incentive framework, niche innovations have been principally implemented in a centralized fashion [37] and supporting policies have been the target of persistent controversies over siting and cost impacts, dampening policy commitments [38]. Furthermore, efforts have been made to reduce electricity use through the introduction of conservation and demand management programs such as time-of-use pricing [39].

The liberalization experience has also left Ontario with a hybrid electricity market. In general, large consumers participate in the electricity market whereas smaller consumers pay a regulated rate. With respect to generators, the current configuration retains a substantial role for public ownership (much of the legacy fleet is publicly owned), though private generators have continued to gain ground with the overarching political preference for private investment and a shift to more investment-friendly project scales. The market, however, does not provide sufficient signals to incite needed levels of private investment in generating assets [40]. Rather, most private investment is government-directed through long-term power purchase agreements, which are added to electricity rates through the so-called "Global Adjustment". This mechanism is meant to account for the difference between the contract price paid to electricity generators and the market price of electricity (see [41] for a more detailed discussion of the Global Adjustment). Presently, the Global Adjustment represents the largest share (85% in 2016) of the total commodity price of electricity for industrial ratepayers, making the pricing regime somewhat opaque. A number of factors are placing upward pressure on electricity prices, including necessary investment to renew aging infrastructure, the phase-out of inexpensive coal-fired power, above-market contracts awarded to cleaner sources, and overcapacity in the context of stagnant demand [42]. Between 2003 and 2016, the inflation-adjusted price of electricity paid by residential consumers has risen by roughly 50% (see Fig. 3). The widely held perception that rising electricity prices are causing affordability and competitiveness issues [43,44] has catalyzed cost containment efforts in electricity system planning and motivated recent reforms. The Liberal government has, for instance, moved to reduce electricity rates by 25% (by shifting investment costs from current rates to long-term government debt) under the 2017 *Fair Hydro Act* [45] and new procurement frameworks such as capacity auctions are being investigated as part of a market renewal process [46].

Beyond market reforms, climate change policies have also been bolstered and are beginning to shape the development of the electricity configuration. Ontario's cap-and-trade program, under the Western Climate Initiative, came into force in January 2017 in order to promote the achievement of near-term (37% below 1990 levels by 2030) and long-term (80% below 1990 levels by 2050) greenhouse gas (GHG)



	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Bioenergy	4.1	9.0	9.0	9.0	55.3	59.5	63.0	112.0	333.0	488.1	488.7
Solar	0	0.3	1.6	40.0	185.5	419.4	645.0	1019.0	1549.0	2117.6	2227.0
Small Hydro	8	8.0	31.0	1028.0	1655.0	1659.9	1710.0	1741.0	2247.0	2273.6	2228.6
Wind	395.1	471.0	704.3	1084.0	1427.7	1958.2	2019.0	2487.0	3498.0	4376.9	4771.0
Natural gas	1236	1225.0	2511.0	4066.0	6293.0	6293.0	7239.0	7173.0	7173.0	7790.4	7976.7

Fig. 2. Electricity capacity additions in Ontario (2006–2016).
Data are drawn from the Independent Electricity System Operator quarterly progress reports.

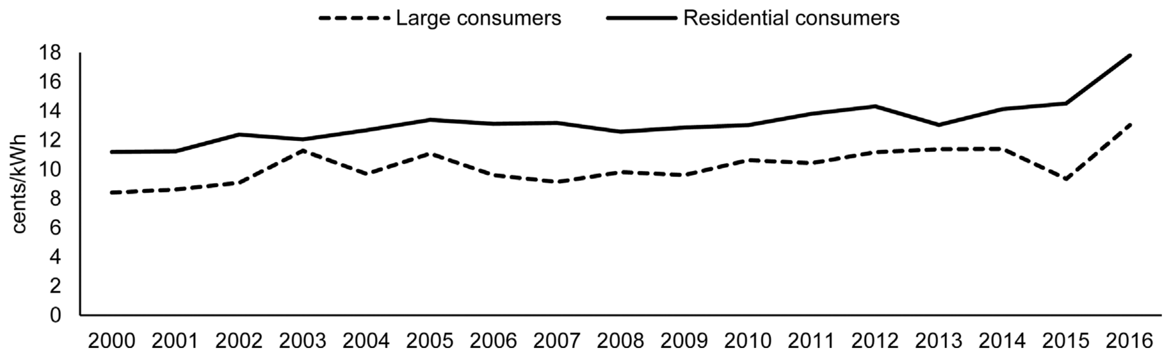


Fig. 3. Price of electricity in Ontario.
Data for this figure are drawn from Hydro-Quebec electricity price comparisons (2000–2016). Residential rates are based on a monthly consumption of 1000 kWh for a household located in Toronto. Industrial rates assume a monthly consumption of 3,060,000 kWh and a power demand of 5000 kW for a company based in Toronto. Rates are in constant 2016 Canadian dollars.

emission reduction targets [47]. As part of this, the Liberals have signalled their support for further societal electrification and set a sales target for electric vehicles of 5% or 14000 automobiles by 2020, supported by a range of incentives for charging infrastructure and vehicle purchases.

The abovementioned patterns have culminated in a relatively low-carbon electricity configuration that appears well-positioned to facilitate broader societal decarbonization. Legacy investments have secured a foundation of baseload nuclear and hydroelectric assets responsible for meeting 60% and 24% of demand, respectively (see Fig. 4). Accounting for more recently deployed new renewables, just over 90% of electricity generation is now low-carbon in nature. The electricity configuration is also characterized by stagnant demand (139 TWh in 2009–137 TWh in 2016) due to the success of conservation programs and declining industrial production [48]. Owing to the reliance on nuclear reactors (which cannot readily be ramped down) and considerable new procurement over the past decade, excess capacity conditions have emerged. Interconnections with neighboring jurisdictions (in particular, to New York, Michigan, and Quebec) have been leveraged to balance the system during periods of oversupply. In 2016, total exports amounted to 21.9 TWh [49].

3.2. Emerging pressures and tensions

The abovementioned socio-technical patterns point to three decarbonization-related incipient pressures and tensions: (1) intensifying concerns about the price of electricity; (2) aging nuclear assets; and (3) the potential re-carbonization of Ontario's electricity configuration. The first pressure revolves around mounting concerns about the rising cost of electricity, which are permeating electricity planning debates. Electricity prices have increasingly become a political flashpoint and policy priority in Ontario [43]. Given the complexity and lack of transparency around electricity pricing (see section 3.1), there is considerable confusion about the drivers of price increases. Some have called attention to the role of nuclear energy in driving up electricity rates [50], whereas others have pointed to emerging renewables and conservation. The Auditor General of Ontario [51], for instance, has suggested that new renewables are a major culprit as developers have been awarded generous contracts that will cost ratepayers $9.2 billion more than "necessary" over their lifespans (i.e., in comparison to less generous incentive rates predating the Feed-in Tariff). Media commentators have jumped on these claims to deride support for new renewables as a form of "green corporate welfare" [52]. Incumbents and regime-aligned actors have also charged emerging renewables as expensive, inefficient, and unnecessary [53,54]. Yielding to these criticisms, the Ontario Liberal government has gradually retreated on policy commitments and attempted to constrain the diffusion of niche innovations by setting annual deployment caps, postponing targets, eliminating procurement streams for larger projects, and transitioning from fixed-price instruments to competitive approaches (see Fig. 5). These tensions around cost containment within the electricity sector are also beginning to play out in the design of future procurement mechanisms. The previously mentioned market renewal process may introduce a capacity auction, which would see generators compete to provide capacity in a forward market but could advantage conventional sources depending on its design [46].

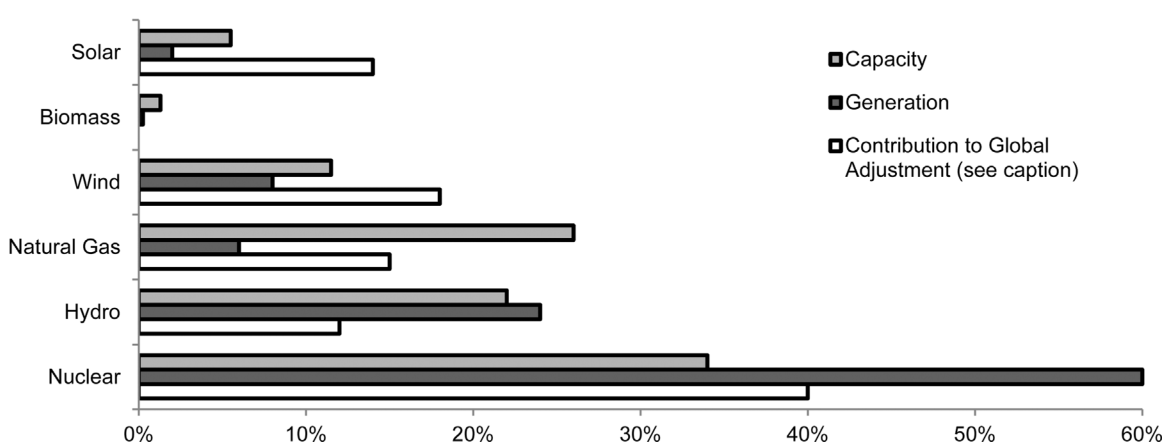


Fig. 4. Projected generation, capacity, and contribution to the Global Adjustment by electricity source in Ontario for 2017.
Data for this figure are from the Ontario Energy Board. The contribution to the Global Adjustment represents the general impact of each source on the price of electricity. The discrepancy between generation and capacity is accounted for by the role each source plays in the system (e.g., nuclear is baseload) and the capacity factor of the various technologies (e.g., generation from solar power depends on the availability of the sun).

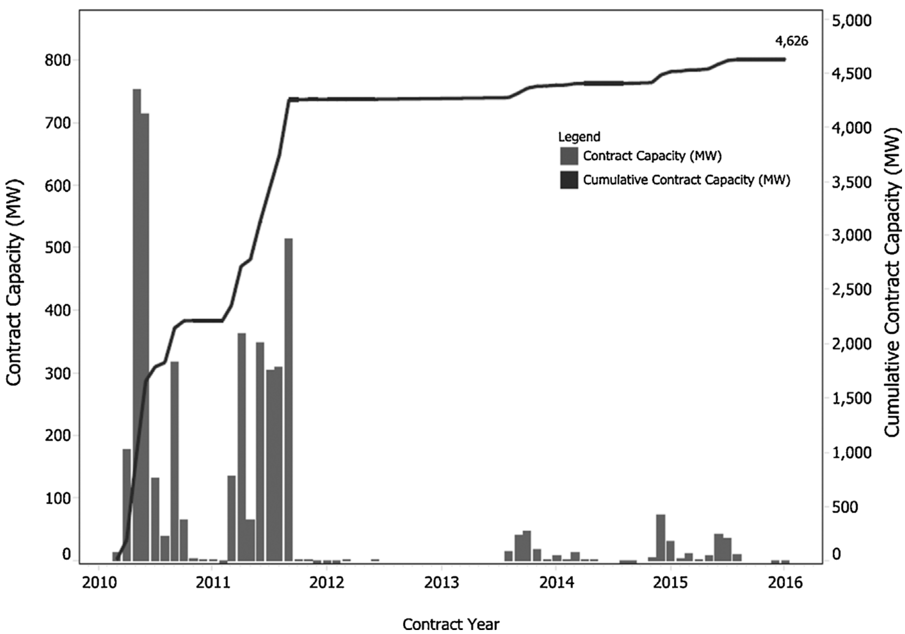


Fig. 5. Contracted and cumulative capacity under the Feed-in Tariff.
This figure is adapted from the Independent Electricity System Operator [55].

Regarding the second pressure, nuclear reactors in the province are reaching the end of their useful lives and require substantial reinvestment. The Ontario Liberal government and incumbents surrounding the electricity regime have advanced a reactor refurbishment schedule (see Table 1). The outcome of this plan will have fundamental implications for low-carbon pathways given the significant role of nuclear in the electricity configuration. Considering the previously mentioned cost containment issues and the history of cost overruns around past nuclear investments in Ontario [33], the refurbishment process is also being subject to increased scrutiny. To this end, the Liberal government has set several conditions (referred to as “off-ramps”) for reactor refurbishments that establish checkpoints where government approval must be reissued for the project to proceed [56]. Although there remains considerable uncertainty about when and how these “off-ramps” might be exercised, the aim is to give decision-makers the ability to adapt or discontinue reactor refurbishments should circumstances change (e.g., if cost-overruns are encountered).

Although more incipient in nature, the final tension concerns the potential erosion of the relatively low-carbon features of Ontario’s electricity configuration. Over the past decade, natural gas-fired units have come to account for 28% of installed capacity. And, while electricity output from this source currently amounts to only 5–10% of overall generation, there is potential for natural gas to take on a more prominent role in the years to come (e.g., to facilitate the refurbishment of nuclear reactors and/or to backup additional variable new renewables). Despite efforts to mitigate natural gas use through peak shaving programs [48] and power import deals with Quebec [57], it remains unclear what role natural gas will play under possible futures (e.g., if nuclear refurbishments are not carried out in full). If the role of natural gas is not addressed, there is potential over time to undo the progress of the coal phase-out and lock-in a more carbon-intensive configuration.

Table 1
Planned nuclear power renewal in Ontario.

Nuclear station/reactor	Scheduled refurbishment/retirement
Pickering	
2 of 6 units	2022 retirement (extended from 2020)
Remaining units	2024 retirement (extended from 2020)
Darlington	
Unit 2	2016–2020 refurbishment
Unit 3	2020–2023 refurbishment
Unit 1	2021–2024 refurbishment
Unit 4	2023–2026 refurbishment
Bruce	
Unit 1	2020–2023 refurbishment
Unit 2	2023–2026 refurbishment
Unit 3	2025–2027 refurbishment
Unit 4	2026–2029 refurbishment
Unit 5	2028–2031 refurbishment
Unit 6	2030–2033 refurbishment

Data for this table are drawn from the Independent Electricity System Operator, Bruce Power, and Ontario Power Generation. Refurbishments are anticipated to extend the operation of Darlington and Bruce stations until at least 2050 and 2060 respectively.

3.3. Critical choices

The above tensions are beginning to open branching points for low-carbon pathways in Ontario’s electricity system. Three critical choices will help define the course adopted at these openings. First, the next decade will involve a sequence of interacting choices about *whether to recommit to nuclear*. Second, while support for new renewables has waned of late, key actors face choices about *whether (and how) to re-invigorate support for emerging renewables*. Third, choices concern *the utilization of natural gas capacity*.

First, Ontario faces critical choices around the planned sequence of nuclear reactor refurbishment. Although the province appears to be proceeding along a nuclear-based low-carbon pathway (with its concomitant financial and environmental concerns), this could change abruptly depending on the outcome of reactor rebuilds and the mobilization of contending interests. Due to the off-ramps integrated within refurbishment agreements, each stage of reactor refurbishment represents an opportunity to derail or reinforce a nuclear-based low-carbon pathway (and the interests at its core such as the nuclear industry and Power Workers’ Union). While the first reactor renewal might proceed, each successive rebuild represents a branching point that is open for challenge and offers opponents (e.g., environmental advocacy groups) a platform to delegitimize the future position of nuclear based on its socio-technical characteristics, interactions with the operation of the system (e.g., conditions of over- or under-supply), and the refurbishment experience (e.g., whether it comes in overbudget). In this fashion, there are still opportunities to influence future choices about nuclear reinvestment and redirect pathways (see Fig. 6). These contests are already playing out in planning debates as, on the one

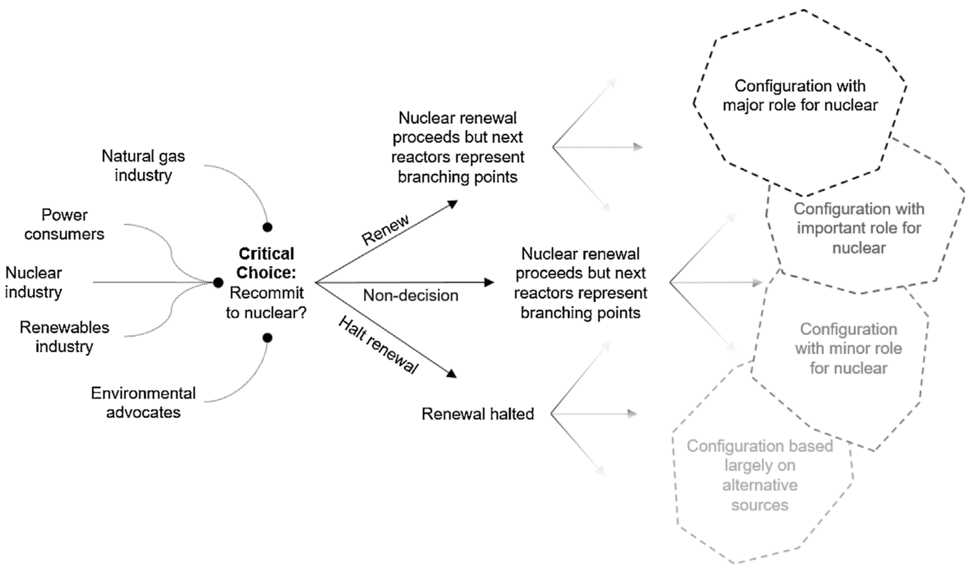


Fig. 6. Schematic representation of branching points around nuclear renewal in Ontario.

hand, incumbents have positioned the refurbishment process as an opportunity to create a "stable, reliable, affordable and non-emitting foundation to pursue further modernization and decarbonization of the province's electricity system and economy" [58]:2. While, on the other hand, challengers have cast nuclear reinvestment as extending commitments to an inflexible legacy source with major environmental and financial costs, which may militate against conservation and distributed power possibilities [59].

Second, critical choices also concern the future of new renewables. As noted, contending interests have struggled to legitimize or delegitimize the place of emerging renewables within the electricity system. These struggles are expected to persist as issues with the current configuration intensify (particularly surrounding the design of market reforms and the negotiation of rising electricity prices and emissions). In this way, there remain opportunities for proponents to recast new renewables as solutions to regime problems, particularly vis-à-vis alternatives (e.g., a nuclear renewal or increased usage of natural gas). However, opportunities to advance renewables could be undermined if niche innovations begin to compete primarily with one another rather than with incumbents for market share and policy support. The allocation of revenue from carbon pricing, for instance, represents one area of potential contestation (especially as other policy support is weakened by cost containment priorities). Similarly, the deployment of associated technologies (e.g., electric vehicles and smart grids), which are slated to receive considerable new support [47], could prove to be a key area of contestation among actors supporting niche technologies or incumbent sources. That is, technologies traditionally viewed as enabling new renewables may be deployed in a fashion to resolve tensions within the electricity configuration rather than encourage additional uptake of new renewables. For example, nuclear advocates have intimated their enthusiasm for electric vehicles (they have sponsored initiatives such as Plug'n Drive Ontario) as they could be deployed in conjunction with smart charging infrastructure to mitigate the inflexibility of reactors and directly encourage electricity consumption, rationalizing investment in nuclear renewal.

Lastly, critical choices are emerging around the future place of natural gas in Ontario given its growing prominence within the electricity configuration (see Fig. 2) and heating sector (roughly three quarters of households in the province use natural gas furnaces). To date, natural gas interests (e.g., distribution firms such as Enbridge and Union Gas) have ensured that they remain part of climate plans [47], successfully challenging a proposed phase-out of fossil fuel heating in homes built after 2030 contained in a draft version of Ontario's Climate Change Action Plan [60]. In doing so, natural gas interests have appealed to cost containment priorities by highlighting the cost-performance features of natural gas. These actors have also pointed to complementarities with incumbent electricity generators (natural gas units as flexible complements to nuclear baseload), emerging sources (natural gas units as backup for variable renewables), and climate objectives [61]. As part of this, a number of low-carbon possibilities for natural gas infrastructure have been advanced, including the use of biogas inputs, fuel switching in heavy duty transportation, and power-to-gas solutions (conversion of surplus renewable or nuclear electricity to produce synthetic gas). Yet, if these low-carbon possibilities are not vigorously pursued, natural gas would likely remain the default option for meeting new heating and electricity needs given its competitiveness and established position. In this way, either an explicit acceptance of natural gas or a non-decision about the future of this fossil fuel would likely allow it to continue to gain market share. And, in this fashion, either of these choices could implicitly lock-in more costly choices later on in the decarbonization pathway (e.g., the vigorous pursuit of carbon capture and storage for gas plants or compensation for stranded assets as gas units are shut down before the end of their useful lives).

Competing interests have an important role in framing these choices and making their implications explicit. For example, new renewable advocates could call into question the place of natural gas and how it might be ramped down (e.g., by extending peak-shaving efforts) or integrated into low-carbon pathways (e.g., by increasingly switching inputs to biogas). Meanwhile, natural gas interests will not be easily dislodged as they actively steer planning decisions away from choices that undermine their interests (e.g., the electrification of home heating) and toward more amenable possibilities (e.g., hydrogen and biogas home heating solutions).

4. The electricity system in Quebec

4.1. Socio-technical patterns

The electricity configuration in Quebec is characterized by a number of important socio-technical patterns, including: (1) the exploitation of rich hydroelectric resources; (2) a commitment to public ownership; (3) the continued provision of low and stable prices; (4) an export orientation to supplement government revenue; and (5) an inclination toward technological and economic development. These patterns emerged out of the nationalization of the electricity system in 1963 [62]. The nationalization was a signature project of the "Quiet Revolution", when the province's French-speaking majority gained economic and political power. "Maîtres chez nous" (Masters of our own

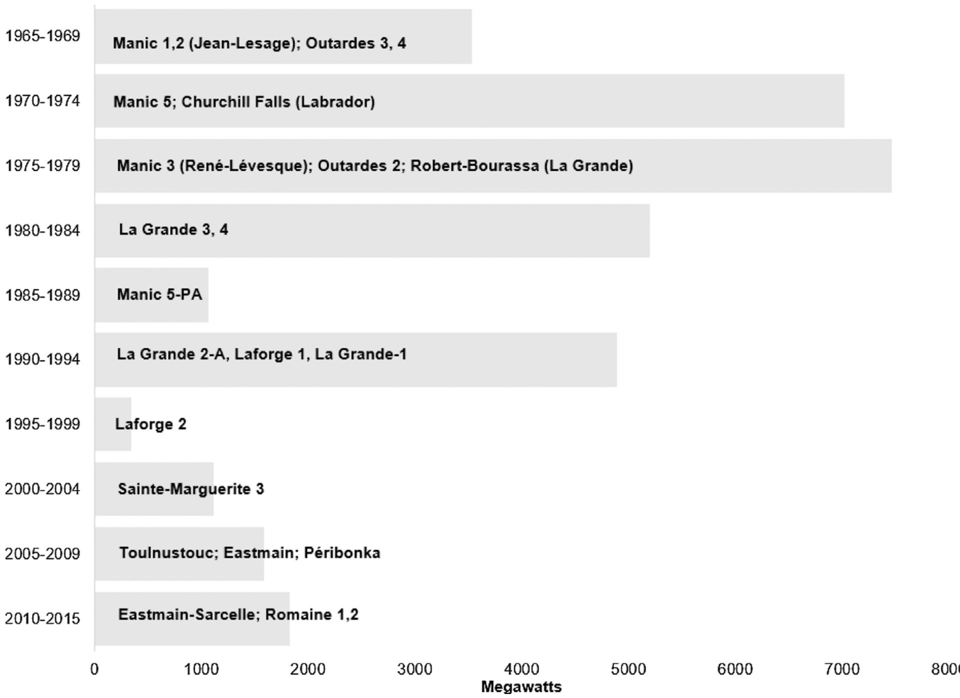


Fig. 7. Hydro-Quebec hydroelectric capacity additions.
Data for this figure are drawn from Hydro-Quebec Production [70]. Three hydro dams are named after former Premiers (Jean-Lesage, Levesque, Bourassa), demonstrating the prominence of these projects in Quebec politics and society.

house) was the slogan of the Liberal Party campaign for electricity nationalization in 1962 [63]. Out of the nationalization experience, Hydro-Quebec emerged as the publicly-owned provincial electricity utility and the dominant actor within the electric power regime. The centralization of system functions within Hydro-Quebec created the organizational means to develop large hydroelectric dams in northern regions and long-distance transmission to southern load centres [64]. This buildout of hydroelectric capacity proceeded rapidly for several decades and is still ongoing albeit at a slower pace (see Fig. 7), resulting in a system that is 99% renewable and 94% hydroelectric (see Fig. 8). Initial hydro development plans paid little attention to affected First Nations communities, leading to resistance, project cancellations, and the negotiation of the first modern treaty in Canada [65,66]. Hydro-Quebec has long demonstrated technological leadership and created opportunities for the francophone middle class [67]. In the 1960s, Hydro-Quebec created the world's first 735-kV transmission line, the largest multiple arch-and-buttress dam in the world (Manic-Outardes), and an electricity research institute [68]. Hydro-Quebec has also used

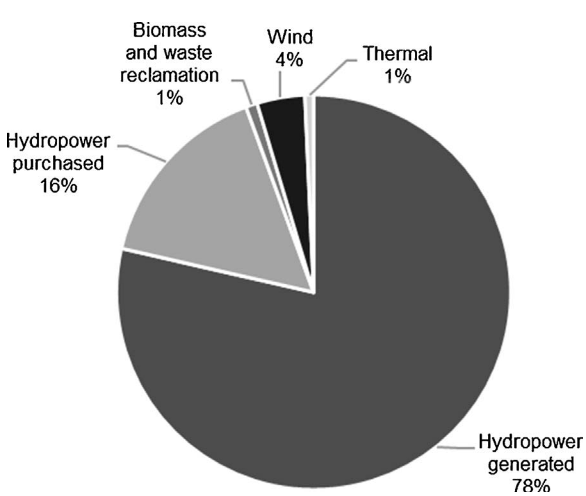


Fig. 8. Hydro-Quebec electricity generation and purchases (2015).
Data for this figure are drawn from Hydro-Quebec [71]. Thermal generation is calculated by subtracting total production/purchases from renewable production/purchases.

its purchasing power to favour domestic businesses, spurring the development of a consulting engineering sector [69].

The electricity configuration in Quebec is also characterized by a "social pact" to use public ownership to deliver stable, low, and regionally uniform electricity rates [72]. Residential electricity rates in Quebec are some of the lowest in North America (see Fig. 9) and low industrial rates are used to incentivize the development of energy-intensive industries such as mining [73]. Hydro-Quebec also exports power to neighboring jurisdictions, especially New England and New York. Given the dispatch flexibility and reservoir storage of its hydro dams, Hydro-Quebec can purchase electricity at low prices and sell during high-price peak periods. The earnings from these export activities produce sizeable dividends for the Quebec government. To comply with US market rules for electricity export, the divisions of Hydro-Quebec were unbundled in the early 2000s and a "heritage contract" was established to maintain low domestic electric prices [74]. Under this contract, Hydro-Quebec Production sells a block of electricity from its legacy assets to Hydro-Quebec Distribution for less than 3 cents/kWh.

With respect to technological and economic development, the Hydro-Quebec research institute (IREQ) works to optimize the power system and develop niche low-carbon energy technologies. From as early as the 1970s, IREQ engaged in testing vertical axis wind turbines and developing off-grid wind-diesel systems. The procurement of commercial-scale wind energy started in the 1990s as a means to manage anticipated energy shortages resulting from hydro project delays and to promote regional economic development. Opposition to the adoption of natural gas-fired sources also helped contribute to wind development [76]. Supported by government procurement and local content rules, tower and blade manufacturing plants were established in the Gaspé region [77]. There is also an electric vehicle niche emerging in Quebec, with about half of the electric vehicles sold in Canada between 2011 and 2015 located in this province [78]. Hydro-Quebec and IREQ have been active in this space, supporting technological innovation and charging infrastructure deployment [79].

The low-carbon electricity configuration that has taken shape in Quebec has positioned the province for the electrification of other energy end-uses. As transport accounts for 43% of the province's GHG emissions, vehicle electrification is expected to play a central role in

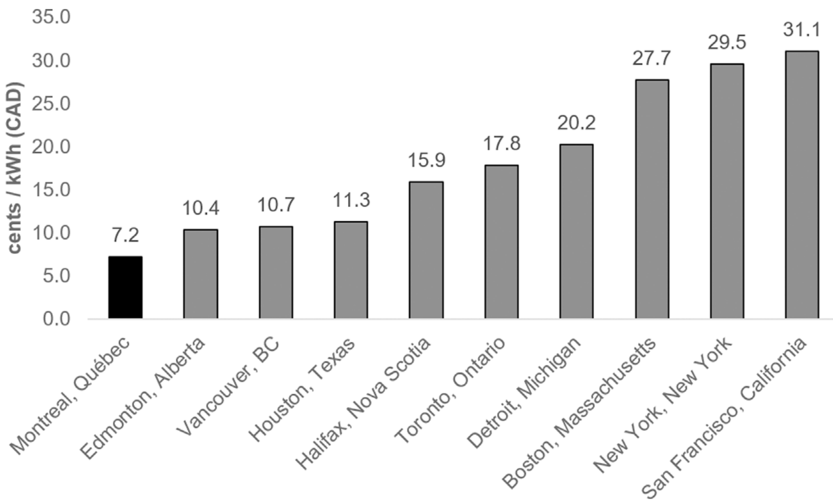


Fig. 9. Residential electricity prices in North American cities (April 2016).
Data for this figure are drawn from Hydro-Quebec [75]. Rates are based on a monthly consumption of 1000 kWh.

achieving GHG emission reduction targets (20% below 1990 by 2020 and 37.5% below 1990 by 2030). The Quebec Liberal administration's 2030 energy strategy aims to make 20% of light-duty vehicles electric by 2030 [80]. A variety of measures have already been introduced in support of this, including zero-emission sales targets for automakers and the use of cap-and-trade revenues (Quebec joined the Western Climate Initiative in 2014) to pursue sustainable transportation options.

4.2. Emerging pressures and tensions

Three pressures and tensions surround Quebec's electricity configuration: (1) diminishing returns for large hydroelectric development; (2) excess electricity supply; and (3) peak demand deficits. The first pressure relates to the diminishing returns facing large hydroelectric development in the province. While there is an estimated 42,400 MW of additional technical hydropower potential in Quebec [81], the 2008 recession and the glut of shale gas have hurt the economic case for developing this capacity by dampening electricity prices within export markets (see Table 2). The Romaine River hydropower project, with a construction schedule between 2009 and 2020, has been a focal point of this controversy. Hydro-Quebec Production [82] initially estimated the levelized cost of the Romaine project at 9.2 cents/kWh, which is well above current export prices. In response to criticisms, Hydro-Quebec [83] later revised this cost estimate to 6.4 cents/kWh, taking into account lower interest rates and removing costs associated with profit margin, dividend, and royalty payments. Experts dispute this later cost estimate [84] and a government appointed energy commission recommended suspending investments in the Romaine project in light of surplus power conditions (discussed in the following paragraph) and falling export prices [85]. Despite this, the previous Parti Québécois government and current Liberal government have continued to support the project and Hydro-Quebec plans to initiate additional hydroelectric development as it foresees rising demand for low-carbon electricity in neighboring regions [86].

Concerning the second pressure, Quebec faces a considerable surplus of electricity due to lower than anticipated energy demand and the procurement of generation above domestic energy needs (see Fig. 10). Beyond pursuing major new hydroelectric developments, Hydro-Quebec has entered into fixed-priced contracts for wind, biomass, and small hydro. The province has, for instance, engaged in solicitations for wind energy (e.g., 800 MW in 2013) aimed at encouraging regional economic development and meeting the government's wind target of 4000 MW [87]. In contrast to the price of legacy hydro at less than 3 cents/kWh under the heritage contract, the average cost of wind solicitations ranges from 7 to 13 cents/kWh [76,88]. Given this cost differential, Hydro-Quebec [89] holds government procurement policies for emerging renewables responsible for more than half of the cost pressures driving recent rate increases. Broader societal actors such as consumer organizations [90,91], free-market think tanks [92], and opinion leaders [93] have also been critical of the government for financing industrial development through electricity rates.

Wind advocates warn that a slow-down in wind procurement will lead to the closure of wind manufacturing facilities and the loss of employment, calling for 300–350 MW of domestic wind development annually to maintain industrial capacity [95,96]. Nevertheless, the Liberal 2030 energy strategy has placed restrictions on small-scale renewables by requiring Hydro-Quebec's distribution unit to halt new purchases of these sources until the electricity surplus is less than 2.5% of demand [80]. In response, wind manufacturing plants in Gaspé commenced layoffs in 2016 [97]. Regarding other emerging sources, a

Table 2
Hydro-Quebec export sales.

	2008	2009	2010	2011	2012	2013	2014	2015	2016
Exports (TWh)	21.1	23	23.3	26.7	35.2	32.2	26.6	29.3	32.6
Export Sales (millions $)	1897	1495	1513	1397	1431	1525	1629	1700	1568
Average Price for Export Sales (cents/kWh)	8.99	6.50	6.49	5.23	4.07	4.74	6.12	5.80	4.81

Data for this table are drawn from Hydro-Quebec annual reports 2008–2016.

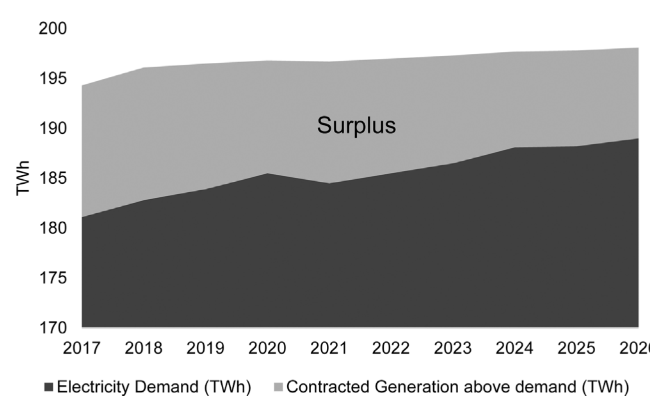


Fig. 10. Forecast of Quebec electricity surplus.
Data for this figure are drawn from Hydro-Quebec Distribution [94]. Note that this figure depicts the electricity surplus over domestic demand excluding exports.

series of small hydro projects developed by municipalities and First Nations were cancelled by the former Parti Québécois government but then relaunched by the current Liberal government. Proponents of small hydro argue that these projects promote economic spin-offs and local energy self-sufficiency [98].

With respect to the third pressure, Quebec experiences capacity deficits during periods of peak demand despite having a surplus of electricity generation in aggregate. Peak periods occur during the winter due in large part to the high penetration of electric heating. This has triggered debates about the options that could be used to address peak capacity shortfalls. Hydro-Quebec has taken steps to secure natural gas-fired assets, signing a seasonal power contract with the Bécancour natural gas plant (an existing privately-owned facility). However, natural gas faces opposition from environmental advocates [99] and the provincial environmental assessment agency has encouraged Hydro-Quebec to explore alternative options such as smart meters and cross-jurisdictional trade [100].

4.3. Critical choices

The above tensions are beginning to open branching points for low-carbon pathways in Quebec's electricity system. Four critical choices will help define the course adopted at these openings. First, actors face choices about *whether to continue to pursue a development agenda based on the expansion of hydroelectricity*. Second, critical choices revolve around *whether to reinvigorate support for other forms of renewable energy*. Third, critical choices concern *how to promote electrification*. Fourth, critical choices relate to *the nature of export strategies and integration with neighboring electricity systems*.

First, Quebec faces critical choices about further expansion of hydroelectricity. As mentioned, continued large hydroelectric development is capturing increasing attention due to its diminishing returns (see Section 4.2). While legacy hydroelectric assets will maintain their prominent position, there is the potential to gradually direct the province's technological development capabilities away from new large hydro projects and toward alternatives types of electricity innovations (see Fig. 11). This choice is intimately related to the electricity system's longstanding role in driving technological and economic development (enshrined by the Quiet Revolution). Historically, the development of hydroelectric and transmission technologies has strengthened Quebec's position and some view this trajectory as having considerable future promise [86]. Yet, others call for the end of this expansionist agenda, advocating Hydro-Quebec to redirect its capabilities toward a broader suite of clean energy technologies such as innovations in energy end-use and small-scale renewables [101,85,102]. Different divisions within Hydro-Quebec and the broader public sector are likely to stake out positions around these choices. On the one hand, the construction division of Hydro-Quebec (*Équipement et services partagés et Société d'énergie de la Baie James*) specializes in large hydroelectric development and has much invested in this trajectory. Researchers in IREQ, on the other hand, have experience with innovations in broader fields such as grid operations and vehicle electrification [76], suggesting that they may be more open to alternative possibilities. The government has also created a new organization called *Transition énergétique Québec* (Energy Transition Quebec) tasked with promoting energy efficiency and achieving climate objectives, which could become an advocate for a more diversified orientation.

A second and related choice concerns the future development of other forms of renewable energy such as wind and small hydro. While historical decisions have helped promote the development of niche renewables and created supportive political coalitions in particular regions of the province, efforts to diminish the electricity surplus have begun to erode this support. A choice not to re-engage with alternative sources could shrink or even eliminate the industrial, political, and technological capabilities embodied within these niches. Moreover, weakening the political and industrial momentum of emerging sources at present could close down future options, making it more difficult to select choices at future branching points that would diversify Quebec's electricity configuration. In contrast, a choice to reinvigorate support for alternative sources may hold more immediate implications for electricity prices, especially if electricity consumption does not pick up. Thus, this choice means confronting potential trade-offs between promoting particular economic development strategies and low-cost electricity.

A third critical choice involves the promotion of electrification. Although there is a broad consensus in favour of electrification given its potential to decarbonize other energy end-uses and alleviate the electricity surplus by expanding demand [103,104], questions still remain about how to promote electrification. Quebec's zero-emission vehicle sales target, for instance, faces opposition from auto manufacturers and dealers who call for stronger consumer incentives rather than regulations [105]. The province has also used proceeds from the cap-and-trade system to expand the natural gas distribution network, triggering criticisms that the government is failing to promote electrification in a way that would challenge natural gas companies [106]. Thus, there are critical choices to be made about the pace and scale of electrification efforts.

Lastly, critical choices also pertain to the nature of export strategies

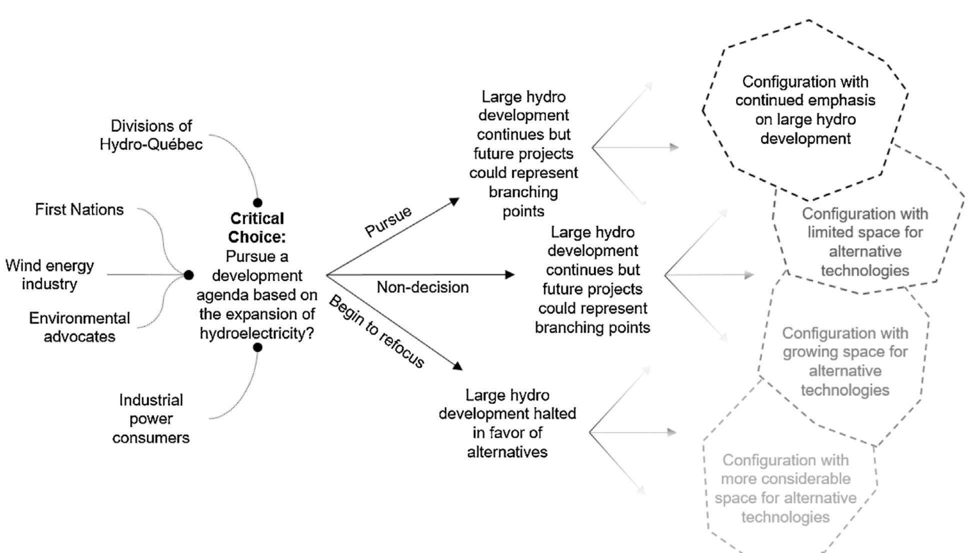


Fig. 11. Schematic representation of branching points around continued large hydroelectric development in Quebec.

and integration with neighboring electricity systems. Expanded electricity exports could create a market for new hydroelectric supply, alleviate the electricity surplus, and enable power resource sharing across jurisdictions to address capacity deficits. Yet, political actors place different emphases on marketing hydroelectricity or a broader mix of sources, which could have implications for Hydro-Quebec's technology development focus and the province's success in securing international markets. As this choice relates to electricity trade, Quebec's future will also depend on decisions taken in neighboring jurisdictions and cross-jurisdictional political coalitions.

In light of restrictions on large hydroelectricity as part of renewable energy standards in many US jurisdictions (e.g., New York and California), Hydro-Quebec and the provincial government have made efforts to lobby neighboring jurisdictions to accept hydroelectricity as a form of renewable energy in their policy targets [107]. These efforts achieved an initial victory when the Vermont legislature recognized large hydroelectric imports as renewable [108]. Even so, political coalitions in neighboring jurisdictions continue to oppose hydroelectric imports because of the environmental impacts of hydro dams and transmission lines as well as fears that imports will crowd out domestic renewable energy sources. In contrast to export strategies focusing on hydroelectricity, wind energy proponents advocate an export strategy that leverages hydroelectricity to backup variable wind power. This export mix would see hydroelectricity complement wind development and could allay concerns about the environmental performance of hydroelectricity [109]. An example of this strategy is the "Vermont Green Line" project, which entails the construction of a high voltage direct current transmission link to New England in order to supply wind from New York state backed up by Quebec hydroelectricity. Another example is Massachusetts' 2016 *Act to Promote Energy Diversity*, which accepts hydro imports but prioritizes projects that combine low-impact renewables with hydroelectricity. Although this policy was subject to less resistance on environmental grounds given its link to wind energy, it was the target of opposition from natural gas generators in Massachusetts [110].

Beyond north-south ties, Quebec may also begin to explore electricity trade with Canadian provinces as a more fundamental part of its export strategy. In 2016, Ontario and Quebec signed a deal to export 2 TWh to Ontario and provide 500 MW of capacity to Quebec in the winter. This will help alleviate Quebec's capacity deficits in the winter months and will also see surplus renewable electricity from Ontario stored within Quebec's reservoirs, demonstrating the potential for hydro to facilitate new renewable electricity development in other jurisdictions. Yet, this agreement falls short of the "grand bargain" envisioned by some, which would see the two provinces cooperate closely on climate goals and use hydro imports as an alternative to nuclear refurbishment in Ontario [111].

5. Discussion and conclusion

5.1. Low-carbon pathways for electricity systems in Quebec and Ontario

Attending to socio-technical patterns, pressures, and choices, this study has identified and interrogated a number of branching points for low-carbon pathways in Quebec and Ontario electricity systems (see Table 3). The positioning of contending interests in relation to critical choices has also been examined, revealing how actors might shape diverging trajectories. While it is not possible to precisely detail how the abovementioned dynamics might interact in orienting specific decarbonization pathways, several prominent features can be observed.

In contrast to most international jurisdictions, the electricity systems examined here are already relatively decarbonized due to legacy investments in low-carbon sources unrelated to climate change, positioning them to begin to decarbonize broader energy end-uses. Quebec, for instance, appears well-situated to leverage its hydroelectric resources to target transportation. Indeed, there is a broad consensus about the electrification of transport with debates mostly centered on pace and scale. Decarbonization pathways for Quebec are also closely tied to electricity trade strategies as enhanced cooperation and interconnection could see the emergence of a North American "supergrid" aimed at balancing various forms of renewable energy sources throughout the region. Unfolding low-carbon pathways in Ontario, on the other hand, not only pose questions about the electrification of transport but also the place of natural gas in heating and electricity sectors. Moreover, there are unresolved questions about established and emerging innovations, which will hinge on the outcomes of key political contests. The delegitimization of nuclear, for instance, might open up an expanded place for conservation, renewables, and trade.

As part of this, Ontario and Quebec have an opportunity to either reinforce longstanding socio-technical arrangements or begin to move toward alternatives. Hydro-Quebec, for instance, may begin to direct its technological development capabilities away from the pursuit of additional large hydro projects. While hydroelectricity will retain its dominance (there is little reason to move away from low-cost legacy hydroelectric assets), Hydro-Quebec could shift its attention to the niche technologies it has helped develop such as wind energy, batteries, and electric vehicles. Yet, such an agenda may also require trade-offs across longstanding priorities to pay government dividends and provide low electricity rates for residential and industrial consumers. Ontario's electricity configuration also appears to be positioned to either reaffirm legacy orientations or veer more strongly toward alternatives, though this choice is somewhat starker given that much of the nuclear fleet is at or nearing the end of its life. Also, Ontario has long faced trade-offs across affordability and the development of energy-related industries (nuclear but more recently new renewables) as low-cost sources were exhausted much earlier in its evolution. While the renewal of nuclear commitments or increased support for renewables-based energy futures will impact affordability, they represent distinct industrial development trajectories and possibilities for technological innovation.

Another important feature relates to the use of fossil fuels for power generation. Whereas constituents in Quebec have resisted the deployment of natural gas-fired units in favor of wind development, this fossil fuel has not yet experienced significant opposition in Ontario. So, Ontario's electricity configuration could ramp up natural gas use as nuclear reactors go offline permanently or for refurbishment (mitigated to some extent by recent agreements around electricity imports from Quebec). This raises questions about whether Ontario might pursue a low-carbon pathway that leverages the established natural gas network (in conjunction with biogas inputs or power-to-gas solutions) to develop domestic electricity storage capabilities in the absence of Quebec's hydroelectric reservoirs. In this fashion, electricity and heating configurations in Ontario might be brought closer together, revealing new battlegrounds for actors (around electric versus natural gas heating, for instance) with implications for potential low-carbon pathways.

Oversupply also represents a shared feature. While electricity configurations in Ontario and Quebec have historically been oriented by expansionist principles, key developments (e.g., dampened economic growth following the financial crisis) have further eroded the basis for electricity expansion. Despite this, both jurisdictions have continued to build generation infrastructure, resulting in oversupply. And, as demand across regional electricity markets has declined, export revenues have also slumped. These conditions have undermined the short-term rationale for new renewable development in both jurisdictions, but have yet to seriously undercut ongoing commitments to legacy sources. Still, if transportation, heating, and other energy end-uses are increasingly electrified as is suggested by existing work on low-carbon pathways [13], concerns over excess supply could one day give way to worries over adequate capacity

A related feature concerns tensions around affordability. While Quebec and Ontario have traditionally benefited from low-cost power, ongoing dynamics have placed upward pressure on electricity prices (e.g., diminishing returns on new hydro, costly nuclear renewals, and

Table 3
Dynamics surrounding branching points for electricity systems in Ontario and Quebec.

Emerging pressures and tensions	Critical choices	Contending interests
Ontario		
Aging nuclear assets	Recommit to nuclear?	Nuclear power industry
Intensifying concerns about rising electricity costs	How to reinvigorate support for new renewables?	Renewable energy industry
Potential re-carbonization as natural gas gains prominence	Utilize natural gas capacity?	Natural gas industry Environmental advocates
		Power consumers
Quebec		
Diminishing returns to large hydroelectric development	Continue to pursue an agenda based on the expansion of hydroelectricity?	Divisions of Hydro-Quebec
Excess electricity supply	Whether to reinvigorate support for other forms of renewable energy?	Industrial power consumers
Peak demand deficits	How to promote electrification?	First Nations
	Nature of export strategies and integration with neighboring electricity systems?	Wind energy industry Environmental advocates

the deployment of more expensive emerging technologies). Consequently, even though electric power rates remain relatively affordable in comparison to jurisdictions in the US and Europe, electricity provision faces increased controversy. The pursuit of low-carbon pathways will need to grapple with these concerns in an attempt to reconcile decarbonization goals with longstanding priorities around affordability.

To be sure, the way pathways unfold will not only link to domestic factors. There are broader developments that will also shape outcomes. Branching points that involve electricity interconnection, for instance, will be dependent on decisions taken in other jurisdictions. Consider, as well, how nuclear accidents, extreme weather events driven by climate change, rapid technological improvements (e.g., the plummeting cost of solar photovoltaics), or even policy shifts in the US (Canada's largest trading partner) could impact upon ongoing struggles over choices and the diverging pathways they help define.

Notwithstanding these broader developments, it is also clear that perennial tensions surrounding centralization and decentralization, conservation and expansion, economic development (as manifested by concerns over electricity rate increases) and environmental performance, and even emerging goals (e.g., more ambitious climate commitments) and longstanding priorities (e.g., the social pact surrounding electricity provision in Quebec) are not likely to be resolved as part of low-carbon pathways. Rather, these different priorities will need to be continually negotiated as pathways unfold. In the near-term actors might, for instance, trade-off environmental performance in favor of lower electricity costs (e.g., as natural gas takes on a larger role in Ontario), but in the long-run this may mean more rapid and potentially expensive emissions reductions will be needed (e.g., as steeper costs are imposed to retrofit, replace, or source alternative inputs for natural gas units).

5.2. Lessons for the practice and theory of decarbonization pathways

Besides these observations about the character of low-carbon pathways for electricity systems in Ontario and Quebec, a number of broader lessons can be drawn. In particular, this study elucidates the role of branching points within unfolding low-carbon pathways, illustrating how branching points are constituted, resolved, and contested over time. It shows how pressures stemming from socio-technical patterns open branching points, which are resolved in a cascading fashion and help define the overarching direction of diverging pathways depending on the sequence of choices taken at each step. Branching points, in this view, represent moments in time when the confluence of particular socio-technical patterns and pressures create openings in path dependencies, which hold the potential to renew or begin to redirect the trajectory of system configurations. By extension, pathways can be understood in terms of the aggregate accumulation of choices at branching points. Importantly, branching points are not only animated by material and social rigidities but also represent key sites of contestation as actors struggle to influence critical choices in a fashion that aligns with their perceived interests. Indeed, our findings further highlight the importance of agency in enacting pathways [9] as actors help shape, and stake out differing positions around, critical choices. In this way, branching points can be understood as loci of latent potential, which can be activated as well as dissipated through sequences of actor moves and countermoves. This suggests that an essential characteristic of branching points is their politically contested nature, which further underscores the dialectical agent-structure relationship that characterizes low-carbon pathways.

It is also worth noting that branching points are not static but rather fluctuate depending on the state of underlying socio-technical patterns and emerging pressures. That is, branching points may be further focused or even occluded by new developments surrounding the evolving socio-technical configuration. Consider, for instance, how a change in political circumstances (e.g., the election of a Conservative government in Ontario's next provincial election) might usher in a more fundamental reorganization of ownership models (e.g., further privatization of Ontario's electricity system) in such a way as to remold branching points (e.g., as a matter of choices around the adjustment of market rules rather than government-directed investments) or even eclipse them entirely (e.g., as decision-makers adopt new priorities). And so, branching points embody contingent and temporally bounded disruptive potentials, which can be overshadowed or intensified by new developments as they reorganize the relationship of forces.

Thinking about pathways in terms of branching points also helps to make the implications and trade-offs of choices more explicit by linking near-term decisions to long-run decarbonized configurations. Given their basis in upsetting established arrangements, transitions have long been understood as embodying serious consequences for power relations and the distribution of material resources [112]. Consider, for instance, how pathways based on further electricity trade and cooperation (e.g., leveraging Quebec's hydro reservoirs to meet demand in nearby jurisdictions) do not solely represent emissions reductions possibilities but also quite fundamentally challenge the position of electricity providers in neighboring regions. Similarly, a choice to renew nuclear reactors in Ontario is not a politically and economically neutral component of decarbonization pathways. Rather, it also reflects a distinct economic trajectory, which embodies considerable support for the Canadian nuclear industry and its estimated 30,000 workers [113]. By focusing on critical choices and branching points, we can begin to lay bare the sequences of essential moments within a broader transition where these consequences are mediated.

Correspondingly, the analysis shows that choices surrounding

incumbents often require an explicitly opposing decision to realize change. Indeed, the branching points emerging around nuclear and natural gas in Ontario as well as hydroelectric development in Quebec suggest that non-decisions are essentially equivalent to support for incumbent sources. That is, a non-decision does not remove established advantages and biases that exist in the configuration (in system operations, for instance). This corroborates recent transition ideas about the importance of simultaneously destabilizing established configurations while supporting niche possibilities [114]. In this view, it is often not enough to stimulate emerging technologies while providing implicit support for incumbents through non-decisions, pointing to the vital role for leadership in actively driving low-carbon change through policy mixes that promote niche potential along with regime destabilization.

Contemplating low-carbon transitions in terms of *branching points, critical choices,* and *pathways* also underscores the plurality of possibilities surrounding decarbonization depending on the sequencing, interaction, and consequences (both foreseen and unforeseen) of decisions. To be sure, this article has touched on these interactions in a necessarily schematic fashion. Even so, it assembles some of the scaffolding to more carefully develop and enhance the transition narratives that help to inform the development of more precise decarbonization pathways. By investigating critical choices at branching points, this research reinforces the need to move beyond broad constraining assumptions that sometimes underlie the development of low-carbon pathways. It also suggests a need for this plurality to be reflected in planning approaches. This may complement emerging work that seeks to bridge modelling and transition perspectives [115]. As transition and modelling approaches are brought into dialogue, socio-technical explorations (like this one) could help identify and interrogate critical choices, which could then be sequenced within more formal and internally-consistent model runs.

In order to inform this future research, several analytical elements can be identified as essential to uncovering branching points and critical choices: (1) an historically embedded understanding of the evolution of a system configuration; (2) knowledge of the fundamental requirements of decarbonization; (3) examination of the socio-technical patterns surrounding a system and the pressures these patterns present; and (4) scrutiny of the political contestation around the issue area. Knowledge of *the historical evolution of a configuration* not only helps situate current system dynamics but also suggests which possibilities can be considered more or less likely (e.g., the public ownership model of Quebec's electricity configuration is unlikely to change in the absence of serious destabilizing developments, whereas Ontario has the potential to move further toward private ownership). The *fundamental requirements of decarbonization* serve to identify core elements of potential low-carbon pathways (e.g., the electrification of heat and/or transport), though more formal modelling would make these requirements even more explicit (by imposing quantified GHG emission constraints). Attending to *socio-technical patterns and pressures* (across practices, policies, and infrastructures) provides a useful framework through which to capture complex processes of change. Lastly, there is value in *exploring opposing voices* (often reflected in media coverage) as this helps shed light on alternative frames, actor positioning, and how interests may come into conflict.

While this study points to a number of useful lessons for the practice and theory of pathways, it also highlights the need for additional research that extends the number of critical choices explored, further scrutinizes interactions among choices, and interrogates how these interactions may present consequences that span different energy-related configurations (e.g., interactions spanning electricity and heating regimes). Indeed, there are an array of important choices that may link even more closely to lifestyle changes (e.g., adopting more ambitious conservation programming that targets practices around indoor heating and cooling) and the structure of broader society (e.g., the pursuit of an economy based on services rather than industry). Together, the approach adopted here has facilitated the analysis of critical choices that will help define the direction taken at branching points for low-carbon pathways unfolding within Canadian electricity systems.

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